The Analyses of Soil Core Samples for Radium in Northern, Central, and Southern Indiana Counties

An Honors Thesis (HONRS 499)

by

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Abstract

Radon-222, commonly called radon, is a colorless, odorless gas that has been linked to increased risks of lung cancer. Radon appears in the natural decay chain of Uranium-238, specifically as a daughter of Radium-226. Radium exists in most soils, though the specific concentration is not a constant. Thus, it is of particular interest in radon studies to examine radium content of soils because it is the source of the radon gas.

In this investigation the United States Department of Agriculture has identified sample sites and obtained soil core samples. In addition, they have determined the soil type and parent material on site. Core samples were taken from sites in eight counties at varying depths, ranging from the surface to as deep as five feet. These samples were analyzed using a gamma-ray spectroscopy system to determine the radium concentration. Analyses are being performed to compare radium activities between sites as well as to study the variation of activity with depth.

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I. Introduction

The isotope radon-222, commonly called radon, is a gas which exists in our atmosphere. Radon is a colorless, odorless, tasteless, inert gas. It is a decay product of uranium-238 and is radioactive. The existence of radon and its daughters in living areas can be dangerous to those who live there. The Surgeon General has stated that radon is the second leading cause of lung cancer in the United States, behind only smoking. Radon is released in soil by the decay of radium-226 (radium). Radium undergoes an alpha emission, and 5% of the decays are followed by a gamma emission which brings it to the ground state of radon. The radon gas rises up from the soil to the atmosphere because of a pressure difference between the soil and the atmosphere.

Once the radon gas enters the atmosphere, it mixes with the countless other gases in the atmosphere. In this situation, the concentration of radon gas never gets high enough to pose a problem. However, when a house gets in the way of the path of radon and allows it an easier route of transport, the gas selects the path of least resistance. Once inside the house, if air circulation is not adequate, the gas will become trapped and the concentration of the radon gas will begin to increase. Radon decays by emitting an alpha particle to form polonium, which in turn decays by alpha emission. Additional decays occur forming more radioactive daughters of radon. The daughters are inhaled into the lungs with normal air molecules, water molecules, or smoke particles. Once inside the lungs, the particles attach themselves to the lung tissue and subsequent decays of the daughters produce the biological cell damage.

Testing for radon is relatively easy and accurate, and a knowledge of the radon level can help to determine whether or not action should be taken to

reduce indoor concentration levels. Indoor radon concentration levels of greater than 4 pCi/l are considered action levels by the Environmental Protection Agency , and the concentration may be lowered through any number of different ways, including adding ventilation, covering sump pumps, and/or sub-slab suction. (U.S. EPA, 1993)

The Ball State University Radon Working Group was formed in 1988. The group included an interdisciplinary group of scientists from Biology, Geology, Natural Resources, and Physics and Astronomy. In addition to testing homes and schools all across Indiana, the group has studied the causes of high radon levels on both an experimental and a theoretical level.

In 1991-1992, David Hines investigated the radium concentration levels in selected soils of Delaware county (Hines, 1992). His results indicated that the Delaware County radium concentration was for the most part similar across Delaware county, and was approximately 2-3 pCi/g. A second study was initiated by Saiful Islam, which investigated the radium concentration of ten counties surrounding Delaware county (Islam et al, 1993). The results of this study indicated that the radium concentration in these samples were similar to those for Delaware county.

The goal of this study, therefore, was to determine the radium concentration across the entire state of Indiana. It was decided that samples of soil would be taken from several regions of the state which differed not only in geography but also in geology. In this manner a preliminary study would be used to determine the need for testing every part of the state for radium content in soils.

II. Theory

A. The Radioactive Decay Chain of Radium

The radium decay chain has only one path. Each decay along that path is either an alpha or a beta decay, followed by subsequent gamma decays to bring the isotope to a stable level. The decay chain of radium is shown in Fig. 1. Radium is an alpha emitter. Radon is also an alpha emitter, as is radon's daughter, the isotope Polonium-218, called Radium-A. Radium-A is followed by two beta emitters, the isotopes Lead-214 and Bismuth-214, called Radium-B and Radium-C, respectively. After Radium-C is yet another alpha emitter, the isotope Polonium-214, which undergoes alpha emission to the isotope Lead-210, which has a half life of just over 22 years, which makes it relatively stable.

The half life of radium is 1600 years. This long half life means that the concentration of radium in soils is relatively constant in time. Therefore, it is safe to assume that over the time period investigated in this study, the concentration of radium will not change due to decay.

The half life of radon is about four days, which means that the radon has adequate time to move through the soil and accumulate inside a house before it has all decayed away. The half-lives of the daughters of radium range from several minutes to less than a millisecond. Once the daughters have attached to the linings of the lungs, these are the times for the decaying nuclei to do their damage.

B. The Radon Transport Mechanism

The movement of the radon gas through the soil is governed by an differential equation called the radon transport equation. It has four terms in it,

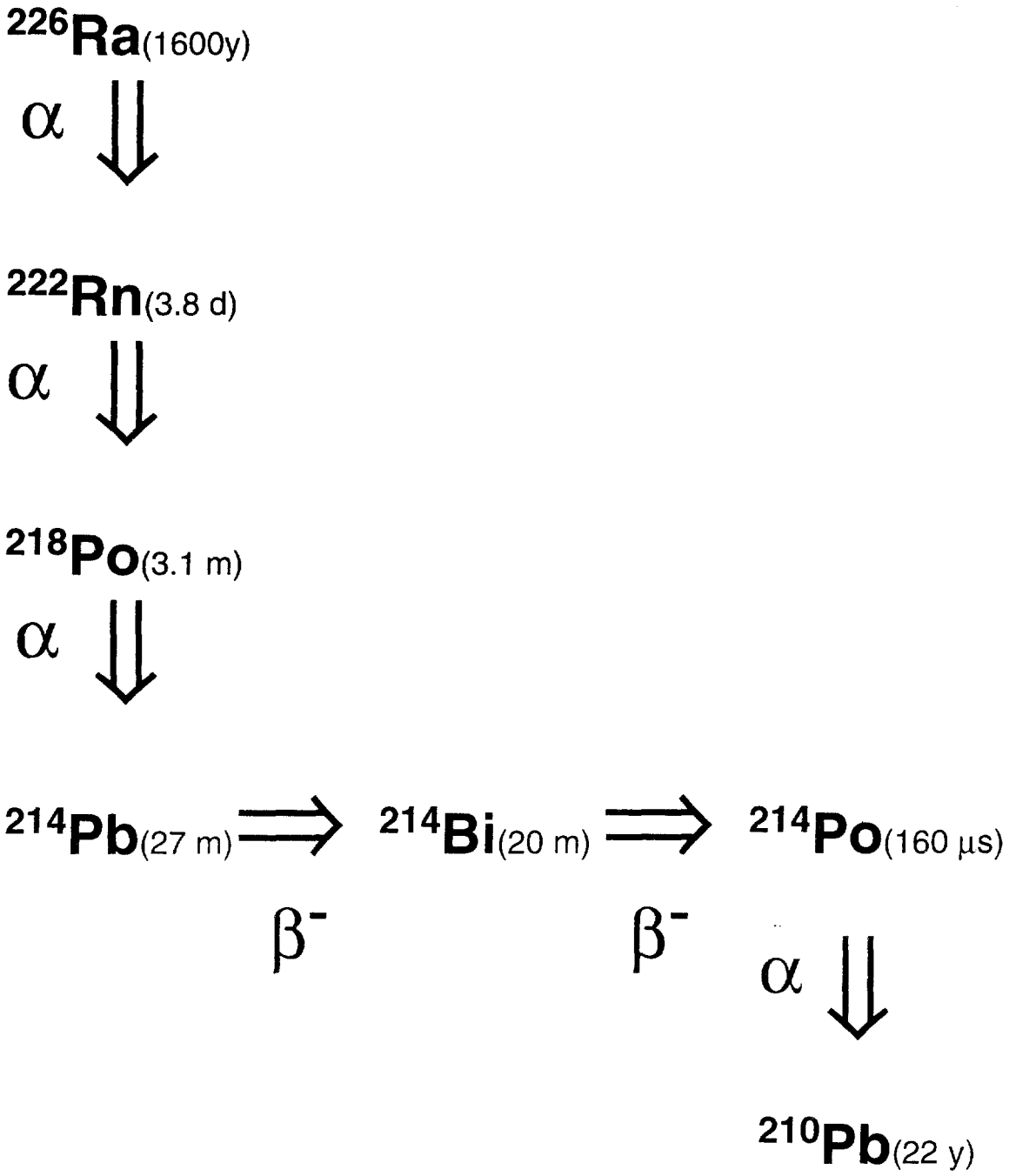


Figure 1: The Radioactive Decay Chain of Radium. This is the decay chain from radium, the source of radon, to the stable isotope lead-210. Decays are represented by arrows, and the type of decay is represented by a symbol either to the left of or below the arrow. Half-lives appear in parenthesis next to the isotope symbols.

namely a diffusion rate, a convection rate, a decay rate, and a generation rate. The radon transport equation is outlined in Fig 2. It has been shown by Brent Puck that for Indiana soils, the primary mode of transportation is diffusion (Puck, 1993). In fact, the diffusion rate is slow enough and the half-life of radon short enough, that after several meters the radon has already decayed. This means that most of the radon coming through the soil into houses is actually only from the first few meters of soil. Thus it is very important to look at radium concentration in the first few meters of soils. One does not have to look very deep to find the source of the radon gas. Of course, the estimation of a few meters can be changed if there is another mode of transport through the soil in addition to diffusion. For instance, if there were a crack underground, the radon gas can move much easier through such paths as opposed to traveling through the soil by diffusion. Therefore, it is also interesting to examine the radium concentrations of soils deeper than just a few meters.

One big term in the radon transport equation is the generation rate. This term determines the actual generation of the radon gas, this term is directly proportional to the activity of the radium in the soil. If there is no radium in the soil, then there will be no radon production. It is the radon generation rate term and specifically the activity of the radium in the soil which is the focus of this study. Although a high radium concentration will not always represent a high indoor radon concentration level and a low radium concentration will not always represent a low indoor radon concentration level, the activity of radium is still important in estimating the potential for high radon levels and when investigating the transport of radon.

Therefore, by examining different soil samples for different counties and different soil types, it will be possible to predict radon levels based on the activity of radium in the soil.

$$\frac{\partial C}{\partial t} = \text{Diffusion} + \text{Convection} + \text{Decay} + \text{Generation}$$

$$\text{Time rate of change of Concentration} = \frac{\partial C}{\partial t}$$

$$\text{Diffusion} = \frac{D}{\varepsilon}\frac{\partial^2 C}{\partial z^2}$$

$$\text{Convection} = -\frac{1}{\varepsilon}\frac{\partial (vC)}{\partial z}$$

$$\text{Decay} = -\lambda C$$

$$\text{Generation} = f\rho A_{Ra}\lambda\frac{1-\varepsilon}{\varepsilon}$$

D = Bulk molecular diffusion coefficient

ε = Soil porosity

v = Velocity of fluid flow

λ = Decay constant

f = Emanation coefficient

ρ = Density of fluid

A_{Ra} = Activity of radium-226 in the soil

Figure 2 : The Radon Transport Equation. The transport of radon through soils is governed by a differential equation containing four terms. It is the last term and specifically the activity of radium-226 in the soil that is of interest in this study.

III. Experimental Procedure

A. Selection Process

There are far too many counties in Indiana (92) for all to be covered in a study of this scale. For this reason, it was decided that different parts of the state would be studied, and generalizations for surrounding counties would be attempted. Soil scientists from the United States Department of Agriculture selected sites for sampling based on geographical and soil differences. It was decided that three different general locations would be chosen. The Environmental Protection Agency had predicted a high radon potential for northeastern Indiana based on previous studies that had been done (Radon Division, 1993). For this reason, Allen County was chosen for this investigation. The soil scientists suspected, due to the nature of the soil, that southeastern Indiana was also an area with high interest. Jennings, Jefferson, Scott, and Clark counties were chosen to represent this part of the state.

Finally, an area was chosen with predicted low levels of radium concentration. The EPA had predicted this area (Delaware county and three surrounding counties: Grant, Blackford, and Randolph counties) would have a high radon potential (Radon Division, 1993) and previous studies done by the Ball State University Radon Working Group agreed with this prediction (Islam et al, 1992). Soils in each location varied in porosity and parent material, so for this reason samples in each county were gathered for this investigation. Figure 3 shows a map of Indiana with the counties examined in this study labeled. In addition, it lists the counties and identifies the number of sites and the number of samples from each county.

Indiana County	Number of Sites	Number of Samples
Allen	35	124
Blackford	1	3
Clark	9	26
Delaware	5	15
Grant	1	3
Jefferson	12	41
Jennings	20	63
Randolph	1	3
Scott	6	23
Total	90	301

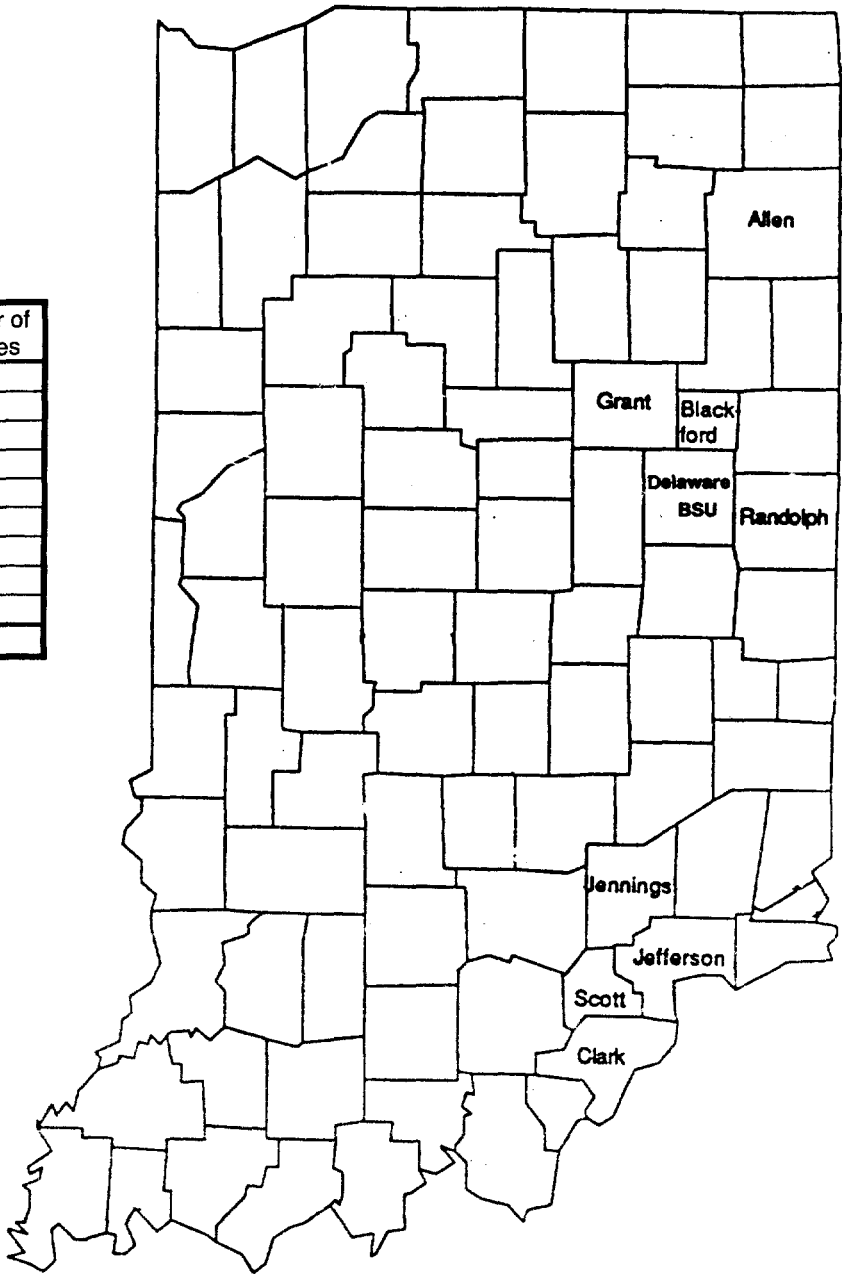


Figure 3: Indiana County Map. All Indiana counties are outlined, however, only the counties which were examined in this study have been labeled. Also included in this figure are the number of sites and number of samples for each county, as well as the total for this entire study. Typically, three or four samples were taken from each site.

B. Acquisition technique

Once the general locations were selected, specific sites were chosen and samples were taken by United States Department of Agriculture personnel at varying depths. Samples were taken at the surface and to depths of five feet, typically between two and three hundred grams were taken for each sample. After being delivered to Ball State University, samples were placed into metal canisters and sealed for analysis.

C. The Spectrometer System

Figure 4 shows a block diagram of the spectrometer system used for this study. The gamma-ray spectrometer system consisted of a detector, a pre-amplifier, an amplifier, a multi-channel analyzer, and two output devices. Two detectors were used for this study. The first was a high resolution intrinsic germanium detector. Because of the resolution of the detector, peaks were easily resolved, though counting times of at least eight hours were required to receive enough counts to ensure adequate statistics. Four other detectors, all sodium-iodide scintillation detectors, were also used. Though the resolution on these detectors was poorer than for the germanium detector, the efficiency was very high. Eight-hour count periods were required for adequate resolution of the gamma-ray photopeaks.

D. Gamma-ray spectra

When radium decays by alpha emission, 95% of the time it decays directly to the ground state. The other 5% of the time, it decays to an unstable level and then gamma decays to the ground state. The gamma-ray energy

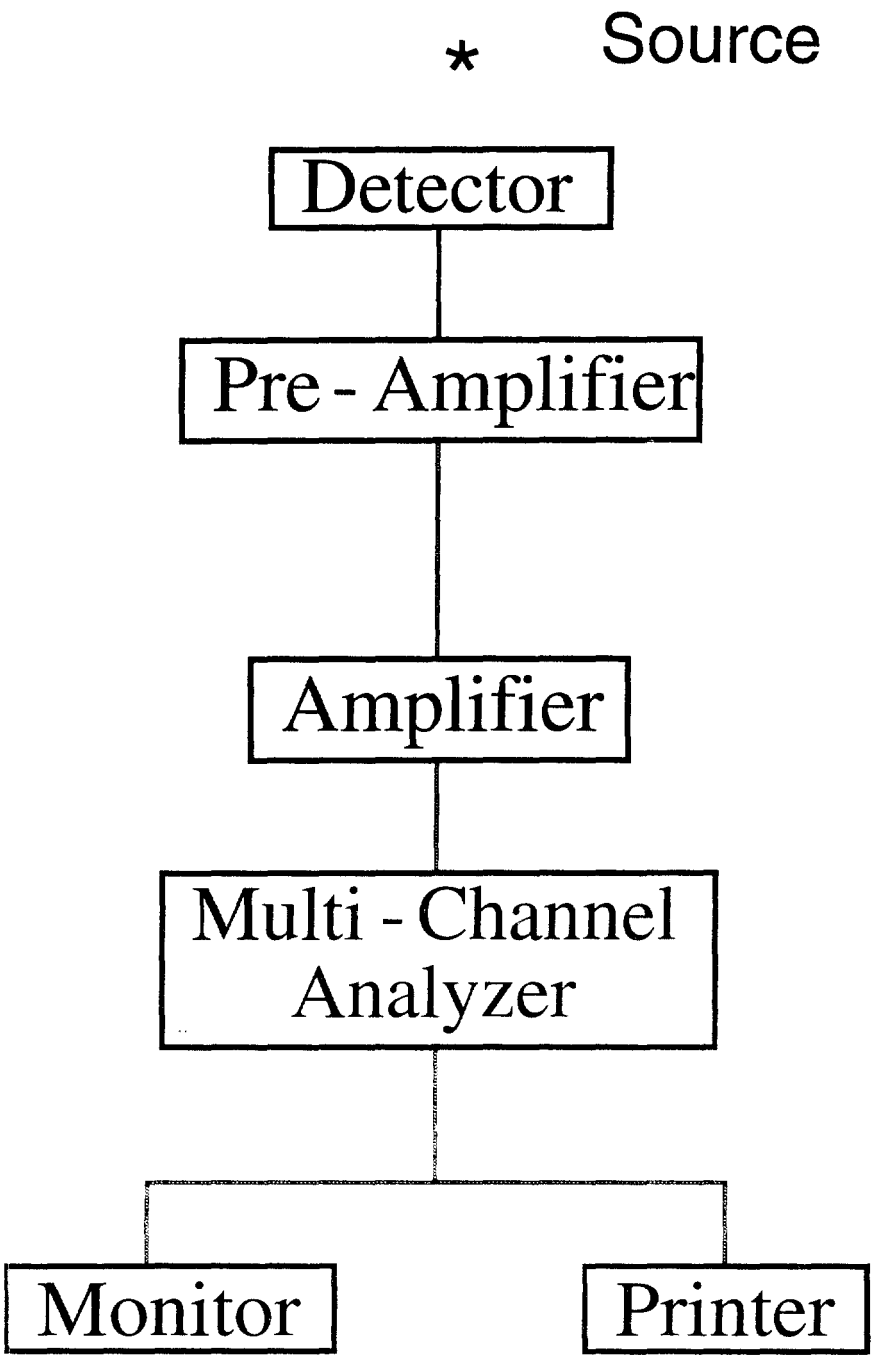


Figure 4: Block Diagram of Spectrometer System. The spectrometer system consists of the six major components shown. The source is placed above the detector, surrounded by a lead house to minimize the room background radiation. The block diagram is identical for both the Germanium and the Sodium-Iodide detectors.

associated with this decay is 186 keV. This gamma ray is a characteristic gamma ray of the radium to radon decay. Not only is this gamma ray always seen in known proportions when the decay occurs, but there are also no other significant naturally-occurring gamma rays in this energy range. Although the decay of radon and the decay of the daughters also emits gamma rays, the measurement of the gamma rays of the radium is an indication of the amount of radon that is in the soil. For this reason, the 186-keV gamma ray was the only one used for examination.

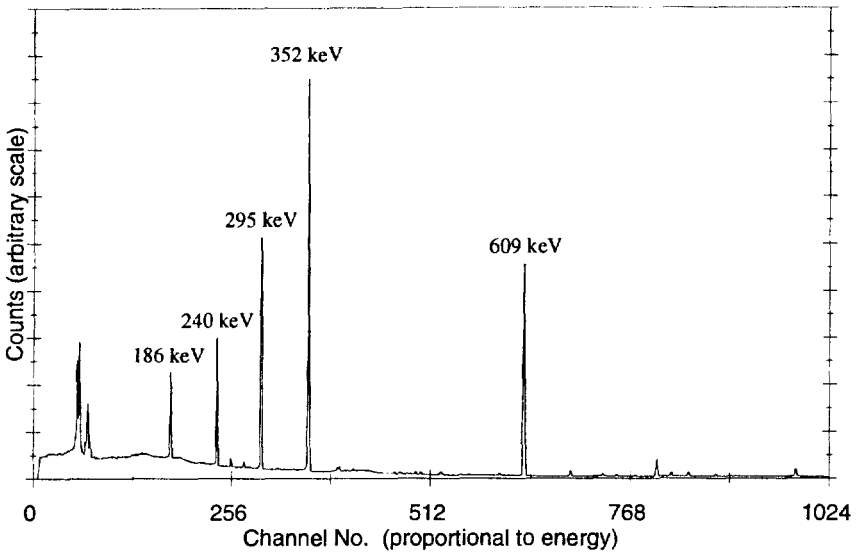
A radium source of known concentration (standard) was used to calibrate the detector. Not only does the standard allow for the determination of the location of the peak, but the number of counts in the 186 keV photo peak is proportional to the activity of the radium. Therefore, when a soil samples was placed in front of the detector, the number of counts in the 186 keV photopeak was compared to the standard and the activity of the sample was determined.

Figure 5 shows two gamma-ray spectra from the germanium detector. The resolution on this detector is very good and the peaks are narrow. For compairson, Fig. 6 are two spectra from the sodium-iodide detector. Here, the peaks spread over many channels and are much broader.

E. Assignment of Statistical Uncertainties

Statistical uncertainties were assigned by assuming Poisson statistics. That is, the uncertainty in any measurement taken with the detector was equal to the square root of the number of counts recorded in the photopeak. These uncertainties propagated through each calculation and an uncertainty was assigned to the activity of each of the soils after the subtraction of room backgrounds.

Standard Radium-226 Spectrum



Sample Allen County Soil Spectrum

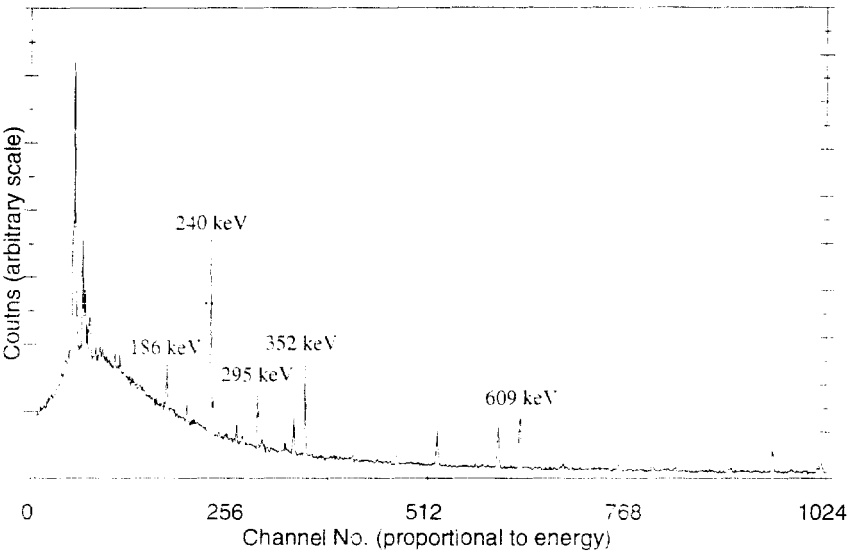


Figure 5: Germanium Detector Gamma-Ray Spectra. The top spectrum was obtained by a radium-226 standard of known activity. The bottom spectrum is a sample soil spectrum from Allen county. The activity of the Allen county sample is consistent with an average Allen county soil sample. The y-axis appears as counts, while the x-axis appears as channel number which is proportional to energy. The y-axes on the two graphs are not the same.

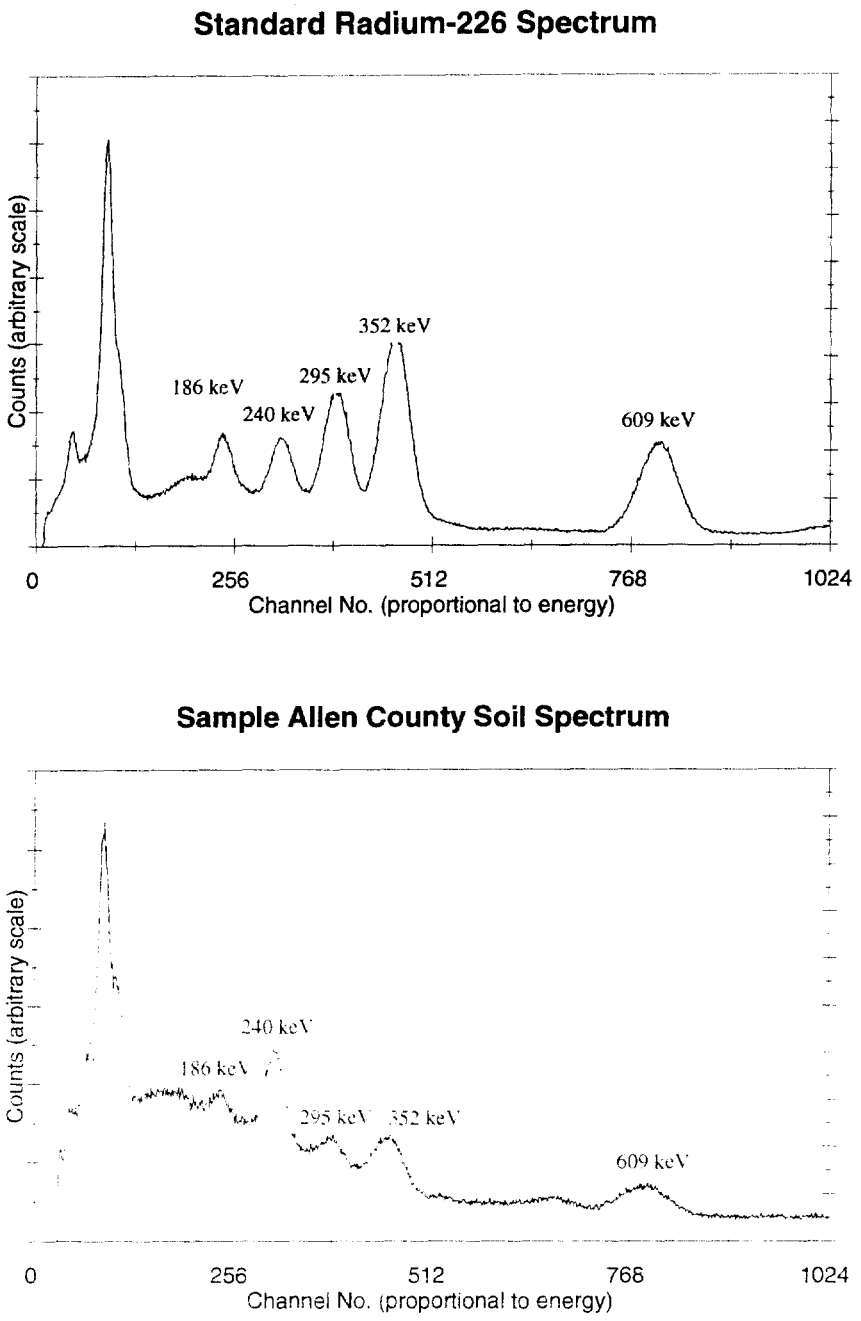


Figure 6: Sodium Iodide Gamma-Ray Spectra. These two spectra are the idential samples as in Figure 6. In contrast to the germanium detector, the peaks on the sodium iodide detector are much wider. Although it is not obvious from these diagrams, the peaks on the sodium iodide detector contain many more counts than on the germanium detector.

IV. Results

The results of the analysis for radium in over three-hundred samples are listed in their entirety in Appendix A. They are listed in alphabetical order by county. Figure 7 shows a summary of some of the results with counties listed in alphabetical order. This graph summarizes three different important details from the data. First of all, the lighter gray bar represents the average surface value from each county. The average surface value is defined as the average of the shallowest samples taken from each site. Although the shallowest sample taken is not always taken from the surface, the shallowest sample is always within a foot deep of the surface. This gives a good indication of the activity at the surface.

The second piece of information listed is the total average, which appears as a black bar. The total average is defined as the average of all samples taken for a single county. The uncertainties on both of these bars are several tenths of a picocurie per gram. The last piece of information listed is the highest activity recorded for each county.

Some counties in Indiana, have "hot spots" of activity. For example, Clark, Jefferson, Jennings, and Scott counties all have some particularly high activities, considering the world average is less than one picocurie per gram. In each of these counties, there are values that are considerably high than those expected. All four of these counties are located in the southeast corner of Indiana. Each of these counties is detailed by at least twenty samples each and for Jennings county, sixty samples.

When examining the data site by site, within each county the data is quite similar. The activity increases with depth. There are sites where this correlation seems weaker, however, when looking at overall trends, the relationship is

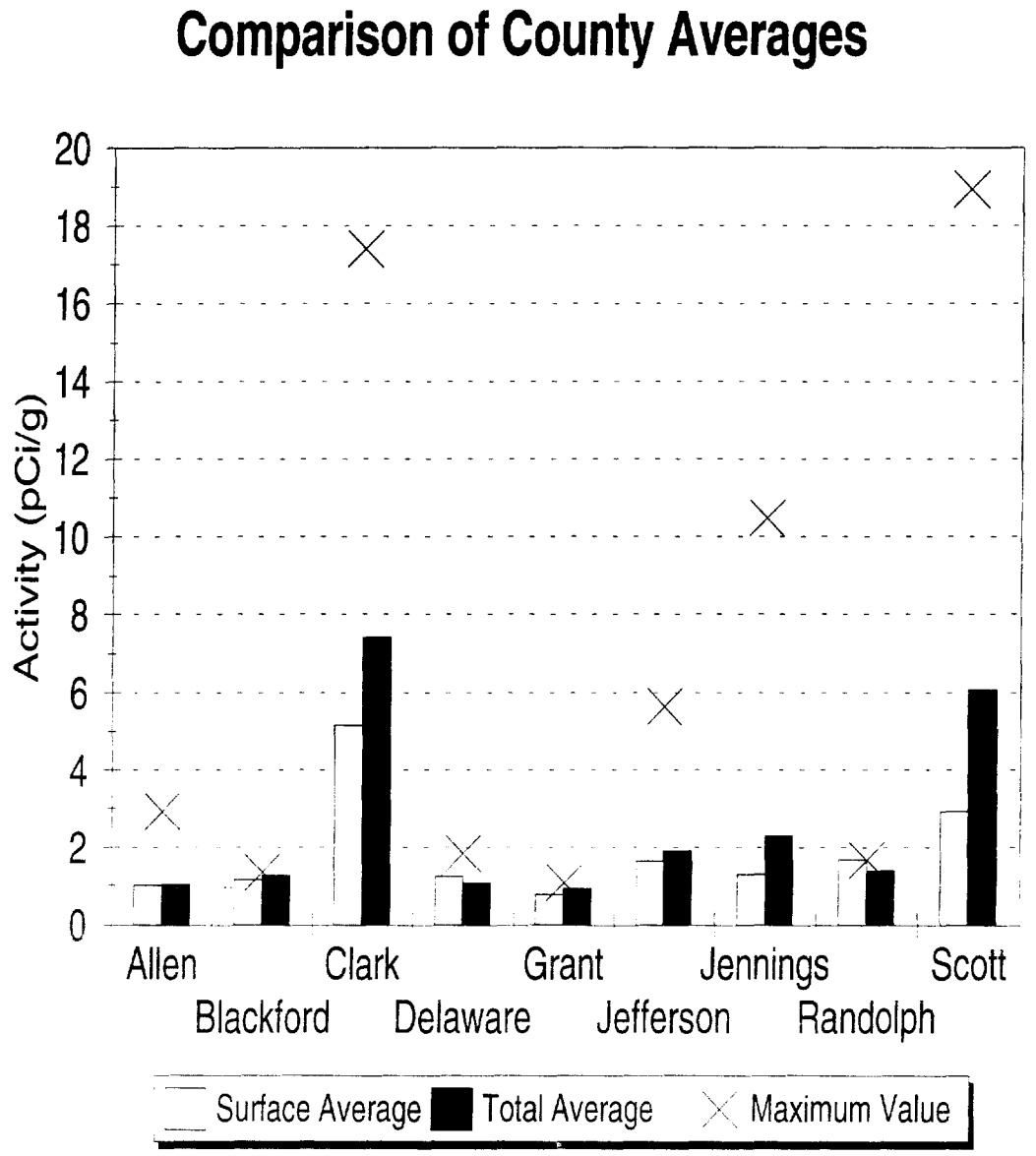


Figure 7: Comparison of County Averages. All ten counties examined by this study are represented on this graph. The lighter gray bars represent the average of all sites in the county using just the shallowest sample, whereas the dark bar represents all samples taken from the county. The X's signify the maximum activity found in that county.

increasing activity with increasing depth. The difference between these counties is the maximum value for the observed activity. Scott and Clark counties both have higher radium levels than Jennings or Jefferson counties.

When examining Fig. 7, it is seen that some counties do not have high radium concentrations. Blackford, Delaware, Grant, and Randolph counties have all three values (surface average, total average, and maximum value) below two picocuries per gram. These four counties are all from the same area of the state and have similar soil types. Delaware county results are based on an analysis of fifteen different samples, whereas Blackford, Grant, and Randolph results are for three samples each.

The few samples that were taken in east-central Indiana agreed with previous results. For this reason, not only can east-central Indiana in general be classified as a low radium concentration area, but there is evidence that it is possible to describe the activity of a county with few samples. If the ultimate goal is to map out the entire state of Indiana, an accurate description of the activity of radium can be attained not with sixty or seventy samples per county, but perhaps with less than ten. This is very important if the above mentioned goal of mapping the entire state is to be reached within a reasonable amount of time.

The Allen county results fall between the high and low groups. Although the surface and total average are about one picocurie per gram, there are some locations that have higher levels of radium than those counties surrounding east-central Indiana. Allen county is located in the northeast corner of Indiana, and it had a predicted high radium concentration. Although the "hot spots" in Allen county have much more activity than the samples from east central Indiana, the activities from this county are much lower than those found in the southeast Indiana group. Perhaps, then, Allen county (being between the high activities of

southeast Indiana and the low activities of east central Indiana) could be called an average county.

Finally, Allen county is of particular importance because it is the result of more than a hundred samples from thirty-five different sites. Even with this large amount of data, the results do not vary significantly from one sample site to another. This suggests that it may be unnecessary to take so many samples and the same results could have been achieved with fewer samples, perhaps even an order of magnitude less. This is a very important finding if a state-wide mapping of radium concentration is eventually considered.

V. Conclusion

Of the three different locations selected in Indiana, very different results were found from each location. Northeast Indiana, which was predicted to have high radon potential, had rather average radium levels (Radon Division, 1993). East central Indiana results agreed with previous results (Islam et al, 1992) and agreed with earlier predictions (Radon Division, 1993). Finally, for southeastern Indiana low radon potential had been predicted, however, extremely high radium levels were observed (Radon Division, 1993).

In terms of radon potential, radium concentration is not the only criterion. Emanation coefficients, permeability of soil, building type, and ventilation are a few of a large list of factors which influence radon levels and which were not examined in this study. However, the results of this study are important in assessing radon potential for the state of Indiana. Three different regions of the state have been successfully examined for radium concentration. Within each of these regions, radium concentration trends were determined. It was also determined that to assess an area of the state for radium concentration in general, fewer samples may be required than were taken for this study. This will make future studies less time-consuming.

This study does not solve the radon problem, nor does it attempt to solve the radon problem. What it does accomplish, however is to provide the ground work for a study which could make mapping the radium concentration of the entire state a solvable problem in a reasonable amount of time. It is not until the entire state has been evaluated for radium concentration and then compared to high indoor radon gas levels that a better correlation between high indoor radon gas levels and radium concentration can be determined. Once this is done, radon levels can be predicted for houses which are in the building stage.

Perhaps more importantly, this study brings radon research one step closer to complete understanding of the radon problem.

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Appendix: Tabulation of Results by County

All data taken has been listed starting on the next page. In some instances, a field has been listed as a zero (0). A zero indicates that the information in that field is not yet available.

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Allen County			
A 1 A	4-8	loess	1.3 +/- 0.2
A 1 B	18-22	till	1.4 +/- 0.1
A 1 C	40-45	till	0.7 +/- 0.2
A 1 D	60-64	lacustrine	1.0 +/- 0.2
A 2 A	8-10	lacustrine	1.3 +/- 0.2
A 2 B	18-22	lacustrine	1.3 +/- 0.1
A 2 C	62-66	lacustrine	1.3 +/- 0.1
A 3 A	8-10	outwash	0.7 +/- 0.2
A 3 B	18-22	outwash	1.0 +/- 0.1
A 3 C	36-40	outwash	0.9 +/- 0.2
A 3 D	58-62	outwash	0.1 +/- 0.3
A 4 A	8-12	outwash	1.1 +/- 0.1
A 4 B	21-26	outwash	0.8 +/- 0.3
A 4 C	42-46	outwash	0.7 +/- 0.1
A 4 D	53-60	outwash	1.2 +/- 0.2
A 5 A	8-11	outwash	0.8 +/- 0.1
A 5 B	22-27	outwash	1.0 +/- 0.3
A 5 C	30-35	lacustrine	0.9 +/- 0.2
A 5 D	50-55	lacustrine	0.9 +/- 0.2
A 6 A	8-12	outwash	1.2 +/- 0.2
A 6 B	18-22	outwash	0.2 +/- 0.3
A 6 C	40-47	outwash	0.9 +/- 0.2
A 6 D	60-64	outwash	0.2 +/- 0.3
A 7 A	8-10	outwash (sediments)	1.4 +/- 0.1
A 7 B	18-22	outwash (sediments)	1.3 +/- 0.2
A 7 C	42-46	lacustrine	0.8 +/- 0.1
A 7 D	67-70	outwash	0.1 +/- 0.1
A 8 A	4-8	Lacustrine	2.2 +/- 0.2
A 8 B	20-24	Lacustrine	2.2 +/- 0.4
A 8 C	52-54	Till	2.6 +/- 0.2
A 9 A	8-10	Outwash	1.3 +/- 0.2

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
A 9 B	20-24	Outwash	1.0 +/- 0.1
A 9 C	44-48	Outwash	0.6 +/- 0.2
A 10 A	8-10	Lacustrine	1.3 +/- 0.1
A 10 B	20-24	Outwash	1.2 +/- 0.3
A 10 C	36-40	Outwash	1.2 +/- 0.1
A 10 D	54-58	Outwash	0.2 +/- 0.1
A 11 A	6-8	Outwash	0.5 +/- 0.1
A 11 B	20-24	Outwash	0.5 +/- 0.3
A 11 C	66-70	Outwash	1.4 +/- 0.2
A 12 A	6-10	Outwash	1.1 +/- 0.1
A 12 B	20-24	Outwash	0.3 +/- 0.3
A 12 C	36-40	Outwash	0.3 +/- 0.2
A 12 D	58-62	Outwash	0.2 +/- 0.2
A 13 A	0-4	Lacustrine	0.8 +/- 0.1
A 13 B	20	Lacustrine	0.6 +/- 0.2
A 13 C	56	Till	1.6 +/- 0.2
A 14 A	0-4	Lacustrine	0.9 +/- 0.1
A 14 B	20	Lacustrine	1.3 +/- 0.2
A 14 C	40	Outwash	1.3 +/- 0.1
A 14 D	55	Outwash	1.0 +/- 0.2
A 15 A	4-8	Outwash	0.4 +/- 0.1
A 15 B	20	Outwash	1.1 +/- 0.2
A 15 C	40-46	Outwash	1.5 +/- 0.1
A 15 D	52-56	Outwash	0.6 +/- 0.1
A 16 A	0-6	Lacustrine	0.9 +/- 0.3
A 16 B	20	Lacustrine	1.1 +/- 0.2
A 16 C	40	Till	1.0 +/- 0.4
A 16 D	44-48	Till	1.3 +/- 0.1
A 17 A	0-4	Outwash	0.2 +/- 0.4
A 17 B	20	Outwash	1.7 +/- 0.1
A 17 C	38-42	Till	0.6 +/- 0.2
A 18 A	0-4	Till	0.2 +/- 0.2

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
A 18 B	20	Till	1.0 +/- 0.2
A 18 C	35	Till	1.9 +/- 0.4
A 19 A	0-4	Lacustrine	1.4 +/- 0.2
A 19 B	20	Lacustrine	1.7 +/- 0.1
A 19 C	48-55	Lacustrine	1.8 +/- 0.1
A 20 A	0-4	Till	1.8 +/- 0.2
A 20 B	20	Till	0.2 +/- 0.2
A 20 C	48-54	Till	0.4 +/- 0.2
A 21 A	0-4	Lacustrine	1.2 +/- 0.1
A 21 B	20	Lacustrine	1.9 +/- 0.2
A 21 C	38	Lacustrine	0.9 +/- 0.2
A 21 D	52	Till	1.5 +/- 0.2
A 22 A	0-4	Lacustrine	0.4 +/- 0.2
A 22 B	20	Lacustrine	1.3 +/- 0.1
A 22 C	52	Till	1.0 +/- 0.3
A 23 A	0-4	Till	0.4 +/- 0.1
A 23 B	20	Till	1.3 +/- 0.3
A 23 C	60	Till	0.3 +/- 0.2
A 24 A	0-4	Outwash	2.3 +/- 0.2
A 24 B	24-28	Outwash	1.2 +/- 0.2
A 24 C	65-70	Till	0.3 +/- 0.1
A 25 A	0-4	Outwash	0.3 +/- 0.2
A 25 B	15-20	Outwash	2.9 +/- 0.2
A 25 C	42-48	Outwash	2.3 +/- 0.3
A 25 D	50-55	Till	0.4 +/- 0.2
A 25 E	55-60	0.00	0.2 +/- 0.5
A 26 A	0-4	0.00	0.5 +/- 0.2
A 26 B	20	0.00	1.3 +/- 0.1
A 26 C	40-45	0.00	1.6 +/- 0.1
A 27 A	0-4	0.00	0.7 +/- 0.2
A 27 B	20	0.00	1.1 +/- 0.1
A 27 C	44-48	0.00	0.2 +/- 0.3

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
A 27 D	54-58	0.00	0.5 +/- 0.3
A 28 A	0-4	0.00	0.8 +/- 0.4
A 28 B	20	0.00	2.2 +/- 0.2
A 28 C	34-38	0.00	1.5 +/- 0.2
A 28 D	50-54	0.00	0.0 +/- 0.3
A 29 A	0-4	0.00	0.6 +/- 0.2
A 29 B	20	0.00	0.4 +/- 0.2
A 29 C	40-45	0.00	0.2 +/- 0.2
A 29 D	54-57	0.00	1.3 +/- 0.3
A 30 A	0-4	0.00	0.6 +/- 0.3
A 30 B	20	0.00	0.9 +/- 0.4
A 30 C	38-42	0.00	2.1 +/- 0.2
A 30 D	45-55	0.00	1.2 +/- 0.3
A 31 A	0-4	0.00	1.9 +/- 0.2
A 31 B	20	0.00	0.9 +/- 0.1
A 31 C	50-60	0.00	2.4 +/- 0.5
A 32 A	0-4	0.00	0.2 +/- 0.4
A 32 B	16-20	0.00	0.9 +/- 0.3
A 32 C	24-30	0.00	0.4 +/- 0.7
A 33 A	0-4	0.00	2.1 +/- 0.3
A 33 B	20	0.00	2.8 +/- 0.2
A 33 C	38-42	0.00	2.1 +/- 0.3
A 33 D	45-50	0.00	0.1 +/- 0.3
A 34 A	0-4	0.00	1.8 +/- 0.1
A 34 B	20	0.00	0.9 +/- 0.2
A 34 C	50-56	0.00	2.2 +/- 0.2
A 35 A	0-4	0.00	1.2 +/- 0.2
A 35 B	20	0.00	0.0 +/- 0.4
A 35 C	50-60	0.00	0.6 +/- 0.3

Number of Sites	35	
Number of Samples	124	
Allen Total Average	1.0	pCi/g

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Blackford County			
S 93 IN 009 001 1	Surface	glynwood	1.1 +/- 0.1
S 93 IN 009 001 4	20.0	glynwood	1.3 +/- 0.1
S 93 IN 009 001 6	60.0	glynwood	1.3 +/- 0.1
Number of Sites	1		
Number of Samples	3		
Grant Total Average	1.3	pCi/g	

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Clark County			
CR 1 A	2-6	loess	1.4 +/- 0.2
CR 1 B	18-22	loess	1.3 +/- 0.2
CR 1 C	50-55	IL till	0.9 +/- 0.1
CR 2 A	2-6	loess	4.9 +/- 0.3
CR 2 B	18-22	loess	4.5 +/- 0.2
CR 2 C	35-40	blackshale	14.6 +/- 0.4
CR 3 A	6-10	blackshale	8.2 +/- 0.3
CR 3 B	10-15	blackshale	16.4 +/- 0.3
CR 4 A	8-12	blackshale	14.7 +/- 0.4
CR 4 B	15-20	blackshale	16.0 +/- 0.5
CR 5 A	2-6	loess	5.9 +/- 0.2
CR 5 B	18-22	blackshale	7.1 +/- 0.3
CR 5 C	36-40	blackshale	9.8 +/- 0.3
CR 6 A	2-6	loess	3.0 +/- 0.2
CR 6 B	18-22	loess	2.6 +/- 0.2
CR 6 C	40-44	blackshale	15.7 +/- 0.6
CR 7 A	2-6	loess	3.2 +/- 0.2
CR 7 B	18-22	loess	3.0 +/- 0.2
CR 7 C	42-46	blackshale	17.4 +/- 0.7
CR 7 D	58-62	blackshale	10.2 +/- 0.6
CR 8 A	2-6	loess	2.4 +/- 0.4
CR 8 B	18-22	loess	5.3 +/- 0.3
CR 8 C	35-40	blackshale	12.9 +/- 0.3
CR 9 A	0-3	blackshale	2.9 +/- 0.4
CR 9 B	18-22	blackshale	2.4 +/- 0.5
CR 9 C	26-30	blackshale	5.6 +/- 0.5
Number of Sites	9		
Number of Samples	26		
Clark Total Average	7.4	pCi/g	

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Delaware County			
IN 035 018 1	0	Glynwood	0.8 +/- 0.3
IN 035 018 4	20	Glynwood	0.5 +/- 0.2
IN 035 018 5	60	Glynwood	0.9 +/- 0.1
IN 035 048 1	0	Glynwood	1.6 +/- 0.1
IN 035 048 3	20	Glynwood	1.3 +/- 0.1
IN 035 048 5	60	Glynwood	1.2 +/- 0.1
IN 035 220 1	0	Glynwood	1.2 +/- 0.1
IN 035 220 3	20	Glynwood	1.8 +/- 0.2
IN 035 220 5	60	GLynwood	1.2 +/- 0.2
IN 035 222 1	0	Glynwood	1.3 +/- 0.1
IN 035 222 3	20	Glynwood	1.2 +/- 0.3
IN 035 222 5	60	Glynwood	0.4 +/- 0.1
IN 035 237 1	0	Glynwood	1.2 +/- 0.1
IN 035 237 3	20	Glynwood	0.1 +/- 0.2
IN 035 237 5	60	Glynwood	1.3 +/- 0.1
Number of Sites	5		
Number of Samples	15		
Delaware Total Average	1.1	pCi/g	

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Grant County			
S 93 IN 053 001 1	surface	glynwood	0.8 +/- 0.1
S 93 IN 053 001 3	20.0	glynwood	0.9 +/- 0.1
S 93 IN 053 001 5	60.0	glynwood	1.1 +/- 0.1
Number of Sites	1		
Number of Samples	3		
Grant Total Average	0.9	pCi/g	

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Jefferson County			
JR 1 A	2-6	loess	1.5 +/- 0.2
JR 1 B	18-22	loess	0.5 +/- 0.4
JR 1 C	45-50	blackshale	0.3 +/- 0.4
JR 1 D	60-65	blackshale	1.7 +/- 0.2
JR 2 A	2-6	loess	1.0 +/- 0.2
JR 2 B	18-24	blackshale	1.1 +/- 0.3
JR 2 C	40-45	blackshale	3.2 +/- 0.6
JR 3 A	10-15	blackshale	1.3 +/- 0.5
JR 3 B	22-24	blackshale	3.1 +/- 0.3
JR 4 A	2-4	loess	1.9 +/- 0.2
JR 4 B	18-22	loess	1.0 +/- 0.2
JR 4 C	34-38	blackshale	1.6 +/- 0.3
JR 4 D	42-46	blackshale	1.2 +/- 0.2
JR 5 A	2-4	loess	0.7 +/- 0.2
JR 5 B	8-12	loess	1.5 +/- 0.1
JR 5 C	18-22	blackshale	1.4 +/- 0.2
JR 5 D	30-34	blackshale	2.2 +/- 0.2
JR 5 E	50-54	blackshale	4.1 +/- 0.3
JR 6 A	2-6	loess	1.7 +/- 0.2
JR 6 B	14-18	blackshale	2.6 +/- 0.2
JR 6 C	20-23	blackshale	2.1 +/- 0.2
JR 7 A	2-6	loess	1.6 +/- 0.2
JR 7 B	18-22	loess	1.3 +/- 0.4
JR 7 C	40-45	blackshale	2.4 +/- 0.4
JR 8 A	2-4	loess	1.6 +/- 0.3
JR 8 B	18-24	loess	0.6 +/- 0.4
JR 8 C	40-45	blackshale	3.1 +/- 0.2
JR 8 D	64-68	blackshale	1.9 +/- 0.2
JR 9 A	4-8	blackshale	2.5 +/- 0.3
JR 9 B	10-12	blackshale	3.2 +/- 0.2

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
JR 10 A	2-6	loess	1.6 +/- 0.2
JR 10 B	18-22	loess	1.3 +/- 0.4
JR 10 C	40-45	blackshale	2.5 +/- 0.4
JR 11 A	2-6	loess	1.7 +/- 0.2
JR 11 B	18-22	loess	1.4 +/- 0.3
JR 11 C	40-45	blackshale	2.3 +/- 0.2
JR 11 D	60-65	blackshale	2.6 +/- 0.2
JR 12 A	2-6	loess	2.1 +/- 0.2
JR 12 B	18-22	loess	1.7 +/- 0.1
JR 12 C	40-45	blackshale	1.3 +/- 0.2
JR 12 D	61-65	blackshale	5.6 +/- 0.3

Number of Sites	12	
Number of Samples	41	
Jefferson Total Average	1.9	pCi/g

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Jennings County			
R 1 A	1-5	loess	2.0 +/- 0.5
R 1 B	18-22	blackshale	7.7 +/- 0.3
R 1 C	25-30	blackshale	9.3 +/- 0.5
R 2 A	5-10	loess	0.8 +/- 0.1
R 2 B	18-22	till	1.4 +/- 0.2
R 2 C	48-52	blackshale	8.1 +/- 0.2
R 2 D	57-60	blackshale	10.5 +/- 0.2
R 3 A	2-8	loess	1.1 +/- 0.1
R 3 B	18-22	loess	1.2 +/- 0.1
R 3 C	40-45	blackshale	2.0 +/- 0.1
R 3 D	53	blackshale	3.0 +/- 0.3
R 4 A	2-12	blackshale	2.1 +/- 0.2
R 4 B	18-22	blackshale	6.1 +/- 0.3
R 5 A	5-10	loess	2.2 +/- 0.1
R 5 B	18-22	blackshale	3.6 +/- 0.2
R 6 A	1-6	loess	0.6 +/- 0.2
R 6 B	18-22	blackshale	1.7 +/- 0.2
R 6 C	55-60	blackshale	2.2 +/- 0.2
R 7 A	1-6	loess	0.2 +/- 0.2
R 7 B	18-22	loess	2.4 +/- 0.1
R 7 C	30-39	blackshale	2.4 +/- 0.3
R 8 A	2-9	loess	1.5 +/- 0.2
R 8 B	18-22	loess	0.6 +/- 0.2
R 8 C	50-55	blackshale	4.0 +/- 0.2
R 9 A	1-7	loess	2.2 +/- 0.2
R 9 B	15-20	blackshale	2.5 +/- 0.2
R 10 A	2-6	loess	1.2 +/- 0.2
R 10 B	15-19	loess	1.1 +/- 0.3
R 10 C	24-29	loess	1.2 +/- 0.1
R 10 D	40-50	till	0.3 +/- 0.2

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
R 10 E	80.0	till	0.6 +/- 0.0
R 11 A	6-10	loess	0.3 +/- 0.2
R 11 B	18-22	loess	1.6 +/- 0.1
R 11 C	50.0	blackshale	4.6 +/- 0.2
R 12 A	2-8	loess	1.1 +/- 0.1
R 12 B	18-22	loess	1.2 +/- 0.1
R 12 C	42-46	blackshale	2.1 +/- 0.1
R 12 D	60.0	blackshale	5.0 +/- 0.2
R 13 A	2-7	loess	1.2 +/- 0.2
R 13 B	15-19	loess	0.0 +/- 0.1
R 13 C	32-37	blackshale	0.6 +/- 0.1
R 13 D	65-70	blackshale	1.7 +/- 0.1
R 14 A	6-10	blackshale	1.8 +/- 0.1
R 14 B	18-22	blackshale	3.0 +/- 0.1
R 15 A	4-7	loess	0.5 +/- 0.2
R 15 B	18-22	loess	0.5 +/- 0.1
R 15 C	40-45	grittty loess	0.9 +/- 0.1
R 15 D	70-75	till palesol	1.2 +/- 0.1
R 16 A	6-9	loess	1.3 +/- 0.1
R 16 B	18-21	loess	2.0 +/- 0.1
R 16 C	32-36	blackshale	2.7 +/- 0.2
R 16 D	50	blackshale	1.5 +/- 0.1
R 17 A	3-5	loess	1.3 +/- 0.1
R 17 B	18-22	blackshale	2.5 +/- 0.1
R 17 C	38-44	blackshale	2.9 +/- 0.2
R 18 A	2-5	loess	0.8 +/- 0.1
R 18 B	18-22	blackshale	2.1 +/- 0.1
R 19 A	3-6	loess	1.7 +/- 0.2
R 19 B	18-22	loess	0.9 +/- 0.3
R 19 C	40-46	blackshale	4.5 +/- 0.1
R 20 A	2-6	loess	1.8 +/- 0.1

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
R 20 B	18-22	loess	0.3 +/- 0.2
R 20 C	33-38	blackshale	3.6 +/- 0.1

Number of Sites	20	
Number of Samples	63	
Jennings Total Average	2.3	pCi/g

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Randolph County			
S 93 IN 135 001 1	Surface	glynwood	1.7 +/- 0.2
S 93 IN 135 001 3	20.0	glynwood	1.4 +/- 0.1
S 93 IN 135 001 4	60.0	glynwood	1.1 +/- 0.1
Number of Sites	1		
Number of Samples	3		
Randolph Total Average	1.4	pCi/g	

Sample Number	Depth (inches)	Parent Material	Activity of Sample (pCi/g)
Scott County			
SR 1 A	2-6	loess	3.0 +/- 0.3
SR 1 B	18-22	blackshale	7.7 +/- 0.2
SR 1 C	30-34	blackshale	18.9 +/- 0.3
SR 2 A	2-6	loess	3.5 +/- 0.2
SR 2 B	18-22	loess	2.3 +/- 0.3
SR 2 C	40-45	blackshale	7.9 +/- 0.2
SR 2 D	54-56	blackshale	13.0 +/- 0.4
SR 3 A	2-6	loess	4.3 +/- 0.2
SR 3 B	18-22	loess	2.7 +/- 0.3
SR 3 C	40-45	blackshale	6.3 +/- 0.2
SR 3 D	58-60	blackshale	10.9 +/- 0.4
SR 4 A	2-6	loess	0.8 +/- 0.4
SR 4 B	18-22	loess	0.6 +/- 0.3
SR 4 C	40-45	till	1.6 +/- 0.4
SR 4 D	55-60	blackshale	2.5 +/- 0.4
SR 4 E	70-75	blackshale	10.4 +/- 0.3
SR 5 A	2-6	loess	3.2 +/- 0.4
SR 5 B	18-22	loess	4.5 +/- 0.2
SR 5 C	40-45	blackshale	4.4 +/- 0.2
SR 6 A	2-6	loess	2.7 +/- 0.3
SR 6 B	18-22	loess	3.6 +/- 0.5
SR 6 C	40-43	blackshale	7.3 +/- 0.3
SR 6 D	45-50	blackshale	17.5 +/- 0.5
Number of Sites	6		
Number of Samples	23		
Scott Total Average	6.1	pCi/g	